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A Review of Optically Controlled Microwave Devices and Circuits

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The combining of optical and microwave technology is imminent, especially the integration of optical and microwave circuit functions on the same circuit or chip. Since the MESFET is the main active component of the GaAs MMIC, it makes sense to explore its properties as an optical detector for the detection of microwave and control signals in fiber optic links. This report is a review of the state of the art in the control of microwave devices and circuits by optical means. First, the use of the MESFET as the optical detector for the control of microwave circuits will be reviewed. Then, investigation for the optical control of microwave devices such as the Gunn device, impact ionization avalanche transit time device (IMPATT), high electron mobility transistor (HEMT), and bipolar transistor will be presented. Finally, different types of photodetectors are discussed and compared with the MESFET.

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1. INTRODUCTION

The combining of optical and microwave technology is imminent, especially the integration of optical and microwave circuit functions on the same circuit or chip. Since the MESFET is the main active component of the GaAs MMIC, it makes sense to explore its properties as an optical detector for the detection of microwave and control signals in fiber optic links. Certainly, other photodetectors such as the PIN, Schottky Barrier, Metal-Semiconductor-Metal (MSM), or photoconductors can be used for these applications. However, the MESFET has become an attractive alternative to these conventional photodetectors because it allows for the direct control of oscillators for injection-locking and mixing.

This report is a review of the state-of-the-art in the control of microwave devices and circuits by optical means. First, the use of the MESFET as the optical detector for the control of microwave circuits will be reviewed. Then, investigation for the optical control of microwave devices such as the Gunn device, impact ionization avalanche transit time device (IMPATT), high electron mobility transistor (HEMT), and bipolar transistor will be presented. In the following section, the literature on the photodetection mechanisms in the MESFET will be reviewed. Finally, different types of photodetectors will be discussed and compared with the MESFET.

2. STATE-OF-THE-ART OF OPTICALLY CONTROLLED GaAs MESFETs

This section reviews the research performed in which the MESFET is used as the optical detector. The DC and microwave characteristics will be reviewed, as well as the optically controlled microwave circuits where direct illumination of the MESFET was employed.

2.1 DC and Microwave Characterization Under Illumination

The first known study on the effects of light on the DC characteristics was performed by Gaffuil *et al.* [1], who measured the change in the pinch-off voltage of a 1 μm MESFET illuminated by a light emitting diode (LED). This voltage change is interpreted as the consequence of the generation of electron-hole pairs in the illuminated space charge region beneath the gate. In the n-type GaAs the excess hole concentration is directly related to the optical intensity and can be used to calculate the induced change in the pinch-off voltage. Variations in g_m and drain current were also measured and found to be 10% and 25% respectively with an optical power of 0.2 mW [3].

DeSalles explored the change in the DC current-voltage characteristics and the microwave S-parameters under illumination [2]. In these experiments, a CW double-heterostructure GaAs/AlGaAs laser diode, operating at 850 nm, was used. This laser provided 2.0 mW of output power which was focused to a 50 μm diameter spot to obtain a power density of 10^5 W/m^2. The MESFET had a 300 μm single gate with a gate length of 0.5 μm.

The change in gate current with increasing illumination was calculated by

$$J_{ph}=q(1-R)\phi\left[\frac{\alpha^3 L_p^2 w_n e^{-\alpha w}}{d^2 L_p^2-1}+\alpha w\right]$$

where q is the electronic charge, R is the reflectivity of the surface, ϕ is the photon flux density, α is the absorption coefficient, L_p is the minority diffusion length, w_n is the undepleted width, and w is the depletion region width. A maximum current of 20 μa was measured with 5 mW of power.

In a second experiment, a 50 K ohm resistor was connected to the gate circuit to take advantage of the external photovoltaic effect, and the DC I-V curves were measured. Under illumination, the device exhibited nearly full drain current (Idss) from pinch-off, due to a photovoltage which is superimposed on the reversed biased gate, thus "pinning" the gate voltage to a forward bias of 0.4 volts. The microwave S-parameters were measured under illumination and compared to the dark conditions using a gate resistor with a value of 1M ohm. Under illumination no significant variations in S_{11}, S_{12}, and S_{22} appeared; however, S_{21} showed a change in magnitude from 2.34 to 2.6 at 2.0 GHz, a change attributed to the change in gm and gate-to-source capacitance (C_{gs}) with light.

Mizuno measured the S-parameters over the frequency range of 3.0 to 8.0 GHz and the drain current as a function of optical power for several gate biases [3]. The optical power from a 2.0 mW fiber coupled laser, operating at 829 nm was controlled by an attenuator. The S-parameters were varied in the same manner as with optical power by electrically changing the drain current. The author suggests that the optical signal acts as another bias port for the control of the microwave characteristics.

The effect of optical illumination on the small signal microwave parameters of the MESFET was studied by Simons and Bashin [4]. The variations in the channel conductance (g_d), C_{gs}, and transconductance (g_m) were computed and compared to measured results. The computations were based on a modification of the basic small signal microwave model equations given by Shur [5,6] for g_m, channel resistance, and C_{gs}. The modification of the equations was to introduce a photovoltage due to illumination of the gate. The transconductance is given as

$$gm=\sqrt{\frac{qn\varepsilon}{2(V_b-V_{gs}+V_{lit})}}v_s w$$

where V_b is the barrier voltage, V_{gs} is the gate-to-source voltage, V_{lit} is the photovoltage, v_s is the saturation velocity, w is the gate width, n is the doping concentration in the channel. The measured transconductance remained unchanged under both dark and illuminated conditions. The computed results show a change in channel conductance of 15% with illumination as well as a similar variation in Cgs.

Gautier *et al.* measured the influence of light on the S-parameters in the region of 2.0 to 8.0 GHz [7]. The results indicate a small change in S_{11}, attributed to a change in C_{gs}, with the largest change occurring in S_{21} near pinch-off (V_{gs}=-2.0 v). Measurements were also taken in the linear region (V_{ds}< 0.5 v). In this region of operation, the ohmic behavior causes a decrease in S_{11} with increasing optical intensity.

2.2 Optically Controlled MESFET Circuits

The technique of direct optical illumination of the MESFET has been applied to control the gain of microwave amplifiers, tuning and injection-locking of oscillators, and mixing or heterodyning of two lasers.

2.2.1 Tuning of MESFET Oscillators

In 1979, Moncrief [8] described a varactor-tuned oscillator used with the varactor removed and the active MESFET oscillator directly illuminated. The oscillator, which operated at 12 GHz, was optically tuned over a 400 MHz range by a laser with an optical power of 100 mW. The shift in frequency was attributed to a 7-fold change in the capacitance of the device. The optical tuning of MESFET oscillators has shown a variation in sensitivity with oscillator configuration [9, 10] at C and X bands. Oscillators (in the common gate and common source configuration) were an order of magnitude more sensitive to light than in the common drain configuration due to changes in the C_{gs} of the device.

2.2.2 Direct Optical Injection-Locked MESFET Oscillators

Direct illumination of the MESFET with an optical source modulated at a frequency close to the oscillation frequency can be used to injection-lock oscillators. Initial observation of direct optical injection-locking of a MESFET oscillator by de Salles and Forrest [11] showed that a 2.35 GHz free running oscillator could be injection-locked over a 5 MHz locking range by direct illumination. The optically converted signal power to the device was estimated at 1 μW.

Buck and Cross have shown optical injection-locking of a 3 GHz MESFET oscillator over a 5 MHz locking range using a fiber optic feed [12]. The best locking range occurred when the the device was biased at the maximum transconductance, indicating that the g_m of the device plays an important role. A novel SPICE model was developed by Warren *et al.* by placing a voltage source in the gate circuit to mirror the photovoltaic effect to simulate optical injection-locking [13]. The model had good agreement with a measured 4.5 MHz locking range.

2.2.3 Gain Control of MESFET Amplifiers

The control of the gain of a MESFET amplifier has also been reported. Gain changes were observed by de Salles. Under pinch-off condition the change in gain observed was 20 dB (10 dB of isolation to 10 of gain), with a 100 M ohm resistor in the gate. Mizuno also observed changes in gain by illumination with no external resistor in the gate circuit, thereby taking advantage of the internal photoeffects. A MESFET was biased at pinch-off (V_{gs}=-3.7 V) and illuminated by a laser. The observed change in gain was from -10 dB to +5 dB in the frequency range of 3.0 to 8.0 GHz, with a change of 0.14 mW of optical power.

2.2.4 Optical Mixing by a MESFET Photodetector

The MESFET has also been considered as an optoelectronic mixer. Rauscher, Goldberg *et al.* have used a MESFET to perform photodetection of an optical signal simultaneously with microwave modulation information and to down-convert the detected signal to an IF frequency [14]. A sub-quarter micron MESFET oscillator was designed for operation at 30 GHz. Optical signals from two GaAlAs laser diodes were combined at the MESFET and demodulated with one of the harmonics of the oscillator to obtain an 89 GHz difference signal from the two lasers. This technique was also used to injection lock a 9.6 GHz MESFET oscillator to a bandwidth of 1.6 MHz [15]. In another experiment, Fetterman illuminated a MESFET with stabilized He-Ne and dye lasers. Through wavelength tuning of the dye laser, beat frequencies of up to 18 GHz were generated, and signals of up to 52 GHz were generated by superimposing an electrical rf signal to the gate [16]. Direct generation of a millimeter wave signal as high as 62 GHz was reported [17]. The technique of optical mixing makes the MESFET useful for the generation of millimeter wave frequencies.

2.3 MESFET as an Optical Detector

Because a sensitive high-speed optical detector is needed in communication, the transient behavior and the frequency response of the MESFET are of much interest. In this section the pulse and frequency response of the MESFET will be discussed.

2.3.1 Pulse Response

In the earliest known work in 1977, describing a MESFET as an optical detector, Baak *et al.* compared a 4-gate MESFET to an avalanche PIN photodetector [18]. The illumination was concentrated in one channel of the MESFET, and a pulse response of 73 ps was measured and compared to the APD, which had a 178 ps response. When the device was completely illuminated, however, a noticeable long tail in the fall time appeared, with the rise time remaining the same at 46 ps, indicating that the response time is a function of the power density.

Several investigators have altered the MESFET to improve the pulse and frequency response. Parer fabricated a MESFET with an indium tin oxide transparent gate metal [19] to facilitate improved coupling of the optical signal

[20]. The reported improvement in the responsivity of 0.4 A/W (external quantum efficiency of 60%) was twice that of previously reported devices. A response time of 20 ps was measured. Gummel describes the removal of the gate and its replacement with an optical waveguide to the conducting channel [21].

2.3.2 Frequency Response

In 1979, Osterwalder *et al.* first measured as an optical detector the frequency response of the MESFET and compared it to an avalanche photodiode (APD) [22] to demodulate multi-gigabit signals in the region of 2 to 4 GHz. The measured frequency response showed that the MESFET had a response similar to the APD up to 4 GHz. Showing that the MESFET has a high gain in the region of 1 MHz to 100 MHz [23], MacDonald presented the gain as a responsivity of 100 A/W to 6 A/W over this frequency range. The frequency response of a MESFET as a switch was measured between 1 MHz to 1300 MHz [24] by changing the drain-to-source voltage from 0 to 7.0 volts. Isolations of 45 dB and 55 dB were observed with an 890 nm and a 783 nm laser, respectively.

2.4 Theoretical and Experimental Photoresponse Studies of the MESFET

Several researchers investigating the photoeffects in the MESFET have come to numerous conclusions as to which effects are responsible for the conversion of the optical signal to an electrical signal. Although no definitive explanation appears in the literature, several photomechanisms are known to contribute to the MESFET's response to an optical input. The literature and the theory on the basic photoeffects in optical detectors indicate that the mechanism that dominates the photoresponse depends on the physical parameters of the MESFET, the electrical bias, and the magnitude and wavelength of the optical input.

In the first work discussing the photomechanisms, Osterwalder *et al.* [25] states that the largest observed effect is due to the generation of electron-hole pairs in the depletion region beneath the gate. The generation of electron-hole pairs induces a photovoltage at the reversed biased junction. This photovoltage is then amplified by the transconductance of the device and detected as photoinduced drain current. Consequently, the change in the voltage needed to pinch-off the channel is determined to be equal to the photovoltage developed at the gate under illumination. Segeta and Mizushima [25] describe the photoresponse in the MESFET as a photodiode followed by an amplifier. A voltage due to the generation of current at the gate under illumination is amplified by the g_m of the device. The voltage change at the gate across a 50 ohm resistor was measured, then multiplied by the g_m of the MESFET and compared to the photoinduced drain current. Soon after, Gammel [26] argued that due to the long wavelength that was used in the previous experiment the optical absorption coefficient is such that many carriers are generated in the substrate and are collected in the gate circuit.

The results that presented the photovoltaic effect as the mechanism for the response of the MESFET were discounted by Gammel & Ballantyne [27], who describe the main effect as photoconductivity in the channel. They observed that the signal present in the gate under pulsed illumination was at least of two orders of magnitude smaller than necessary to explain the observed drain current. They also discounted a second mechanism, the modulation of the depletion region under the gate due to the existence of a signal beyond pinch-off. They also stated that the gate can be removed as it plays no part in the response. They attempted to change the device structure by fabricating a MESFET without a gate and replacing it with an optical waveguide. With an optical source at 620 nm, this device had a pulse response of 150 ps and a typical internal gain of 5. The gain was shown to increase, with increasing bias voltage (0.0 to 3.0 volts) due to the decrease in the transit time of the electrons, and then the gain saturated at peak electron velocity (aprox. 4.0 volts). They also observed that the response was higher at the drain side due to the higher internal fields.

The analysis of photoconductive gain in the channel of the MESFET has been explored by Darling [28, 29]. The results indicate that the standard optical gain expression based on constant mobility, uniform fields, or uniform channel thickness may be in error by as much as 50 to 100%. In a typical GaAs MESFET, the optical gain of 13-15 in the channel has been calculated by Baak, *et al.* [30]. However, due to nonuniform generation, the gain had been shown to be less. Optical gain in the channel is also presented as a function of drain-to-source voltage (Vds). The optical gain showed a significant increase with Vds and then fell rapidly beyond 0.5 volts or 10^4 V/cm, a change attributed to the mobility ratio approaching unity in GaAs at the saturation velocity. Darling's results indicate that the optical gain in the MESFET is dependent on the power level and on Vds. The optical gain measured was in the range of 40 to 70, much larger than one would expect with only photoconductive gain in the channel. Therefore, another mechanism must exist. The largest observable photoresponse was near pinch-off where the channel is small. The high values of gain at large Vgs are indicative of a photovoltaic effect.

Edwards [31] reported that the major effect was channel width modulation with illumination. This effect, the internal photovoltaic effect, is due to the development of a voltage at the barrier between the epitaxial layer and the substrate with illumination. In this demonstration of the internal photovoltaic effect, the gate of a MESFET was removed and the photocurrent was measured. The result was compared to a device with the gate and was shown to be equal. Also, a measurement of this voltage was performed using a high impedance voltmeter between the source and the substrate. The voltage curve as a function of optical power followed the optically induced drain current, leading to the belief that the current is a direct function of this voltage and the transconductance of the device.

Noad *et al.* performed a study in which they determined that the mechanisms for photodetection in the MESFET were frequency dependent [32]. At high frequencies, photoconductivity in the channel is dominant; and at low frequencies, the photovoltaic effect at the channel-substrate interface which caused the large gains observed dominates. The frequency response of the MESFET from 100 MHz to 1.3 GHz was measured using 783 nm and 840 nm lasers. The observed response indicates that there exists a gain of 2.5 for frequencies beyond 1 GHz which is in agreement with calculated results. At low frequencies, an e-beam was used to scan the device and observe the current response as a function of position and depth. Noad measured a significantly large response with the beam when scanned away from the depletion region between the gate and the drain. The large response indicates that another mechanism exists other than the modulation of the depletion width by illumination. The authors concluded that the reaction is due to the reduction in the potential that exists at the channel-substrate interface.

The change in the channel-substrate barrier potential, or backgating, and the effect of traps was investigated by Papaionannou and Forrest [33]. The aim of their work was to take into account what factors determine the channel majority lifetime, trapping into deep levels and backgating effects, and how these factors effect the photoresponse. The effects of traps on the response is manifested by a long tail in response to a light pulse. Since numerous hole trap levels can exist in GaAs MESFET material due to lattice defects or unintentional contamination of the active layer, the frequency response should show an almost continuous decrease, and the slope should not necessarily follow a 20 dB/Decade roll-off. A common trap level in GaAs MESFETs occurs due to Cr(HL12), with a cut-off of 11 MHz. Backgating has been observed in MESFETs by illumination of the barrier at the channel-substrate interface. Measurements show that the response has a low frequency in the kilohertz region due to the high substrate resistance and capacitance, and that at high frequencies the effect is minimal. A generalized model of the photoeffects in the MESFET, presented by Adibi *et al.*, was based on circuit theory [34].

3. STATE-OF-THE-ART OF OPTICALLY CONTROLLED MICROWAVE DEVICES

The optical control of other microwave devices such as Gunn, IMPATT, mixer diodes, and three-terminal devices such as HEMTs and HBTs has generated great interest. In the section that follows, the optical control of these devices will be reviewed.

3.1 Optical Control of Gunn Devices

The Gunn device was the first microwave semiconductor to be controlled optically [35]. The objective was to optically generate carriers in the active region thereby lowering the electric field which controls the dipole formation position or time. By direct illumination of the active layer of a GaAs Gunn device oscillating at 501.5 MHz, Califano was able to tune 12 MHz with a power density of 25 mW/cm^2 from a tungsten lamp [36]. The response of the Gunn device to changes in the frequency of oscillation was shown to have a long time constant in the order of 100 ns [37]. The long time constant was possibly due to the emptying of trap levels in the material by illumination, and it would account for the wide variation in response of the individual devices. Haydl demonstrated that the oscillation frequency could be controlled by continuously illuminating the device and applying a shadowed region near the anode [38]. Dipoles formed and matured under the shadowed region due to the high electric field. The oscillation frequency, based on the transit time, could be controlled by changing the distance from the shadowed region to the anode. The period of oscillation changed from 5 to 25 ns by moving the shadow 250 to 1500 μm from the anode.

Haydl and Solomon grew low carrier concentration devices in which coherent Gunn oscillations were observed when illuminated by a white light source [39]. The improvement in the oscillation was characteristic of an increase in the peak-to-valley ratio which showed an increase from 1.6 to 2 under illumination. Adams *et al.* biased a 10 μm long Gunn device to below threshold and illuminated the active region to trigger domain formation [40]. Each 1 ns pulse from a He-Ne laser initiated a single domain formation. Gunn oscillations were also triggered by radiation with a 1.06 μm signal [41] due to traps located in the Cr:GaAs substrate. Carruthers *et al.* have demonstrated short bursts of microwave oscillation from a picosecond optical pulse [42, 43].

By changing the position of the optical spot, they observed oscillation frequency changes from 6.5 to 10.5 GHz. Nurmikko *et al.* demonstrated that intense radiation from a 10.6 μm laser could enhance intervalley carrier transfer and induce Gunn oscillation by direct carrier heating [44].

3.2 Optical Control of IMPATT Devices

IMPATTs have three distinct optical control modes. The first uses an optical signal of low intensity to tune the resonant frequency. The second involves the illumination of the IMPATT with a modulated signal close to the natural resonant frequency for the purpose of injection-locking the oscillator. The third mode, optical switching, requires an optical signal which alters the negative resistance properties of the device, thus driving it into or out of oscillation.

Illuminating the IMPATT alters the timing of the avalanche cycle by generating electron-hole pairs within the device, thus producing a change in the frequency of oscillation. Vyas was first to show that leakage current enhancement of IMPATTs by illumination tuned an IMPATT oscillator 10 MHz [45]. The tuning of IMPATT oscillators has been demonstrated up to W-band by Seeds, whereby a 91.83 GHz oscillator was tuned 9.4 MHz with an optically generated current of 20 μA [46]. A study of the effect of optical illumination on the trapped plasma avalanche triggered transit (TRAPATT) device showed that the optical signal enhances the carrier avalanche process which acts to control the dynamics of the plasma [47].

The initial observation of optical injection-locking of an X-Band IMPATT oscillator was presented by Seeds and Forrest [48]. An IMPATT operating at 7.8 GHz was injection-locked by a subharmonic (2.6 GHz) of a laser to achieve a 1 MHz locking bandwidth. Optical injection-locking was also performed by Yen using several different subharmonics, up to the sixth, to lock a free running oscillator at 8.116 GHz [49]. Yen also observed that tuning of the oscillator's frequency by the optical signal could be positive or negative depending on the bias and circuit conditions. Seeds and Forrest have shown a significant reduction in FM noise of GaAs and Si IMPATTs by optical illumination [50]. Vyas *et al.* demonstrated that there can be an order of magnitude difference in the sensitivity of RF characteristics to the type of photocurrent component, e.g., hole or electron saturation currents [51, 52].

Yen *et al.* studied the enhancement and the reduction of the microwave output power by an optical signal as a function of bias, oscillation frequency, and the intensity of the optical signal [53].

3.3 Optical Control of HEMT Devices

Concerning the effect of optical illumination on the HEMT, Simons and Bhasin were the first to measure the drain current and the microwave S-parameters of an AlGaAs/GaAs HEMT under illumination [54]. An average change in the gain of the HEMT of 2.8 dB at 26.5 GHz was measured with 1.7 mW/cm^2 of optical power density. The pulse response of an AlGaAs/GaAs HEMT under illumination was found to be 22 ps by Umeda *et al.* [55]. Fetterman used a modulation doped FET as a picosecond sampling gate with a rise time of 12 ps and a response time of 27 ps [56].

3.4 Optical Control of Bipolar Transistor Devices

Although not as popular as other devices for microwave applications, bipolar transistors have been optically controlled. Yen *et al.* have demonstrated optical injection locking and switching of a Si bipolar transistor oscillator [57]. A transistor oscillator operating at 1.85 GHz was injection-locked by a sub-harmonic of 98 MHz. When illuminated by a laser with 0.3 mW of optical power, the base current increased by 10 μA. Thus, by biasing the transistor below the threshold for oscillation, the optical signal will cause the device to oscillate.

3.5 Summary

Optical control of active devices has shown that the microwave performance can be significantly altered. Thus, exploiting the interaction of light and microwaves will introduce an additional port or degree of freedom. Control functions such as tuning, injection-locking of oscillators, gain control of amplifiers, phase shifting, switching, and mixing can be accomplished optically, allowing for the remote control of the microwave circuit function with less sensitivity to EMI and EMP and higher isolation between channels than with metallic cables.

The limiting factor in the use of *direct* optical control which affects all the microwave devices described in this review is the poor optical coupling. As reports have shown, calculated or measured optical coupling can be as low as 1% or as high as 15% of the optical signal coupled into the microwave device. Another alternative to the control of microwave devices is the *indirect* method, which requires conversion of the optical signal by a photodetector such as a PIN, followed by amplification of the detected signal. Although this approach leads to complicated circuits, it requires less optical power and is not restricted to the 0.85 μm wavelength for GaAs MMICs.

4. HIGH SPEED OPTICAL DETECTORS

The design of high speed receivers has been presented, with comparisons of photodetector types [58, 59], and so has a study on integrated photodetectors [60]. Many types of photodetectors exist; however, only those with applications to microwave and millimeter wave systems and monolithic integration are reviewed here. A comparison between photoconductors and photodiodes has been presented [61], in which the frequency response and noise performance were analyzed up to the microwave region, showing that the photodiode had superior performance at low optical power levels, while the photoconductor gave comparable or improved performance at higher light levels.

4.1 Photoconductors

Very high speed GaAs photoconductive detectors have been fabricated with response times in the picosecond range. Roth *et al.* have reported a 68 ps response time for a 3 μm thick detector with a 3 μm by 30 μm active area [62]. Auston *et al.* have reported less than 10 ps responses in amorphous Si [63, 64] for use in measurement systems. Photoconductive detectors have been fabricated on n-type GaAs for monolithic receiver applications with a rise time of 5 ps [65]. The impedance properties of GaAs ion-implant photoconductive devices was measured [66].

Planar photoconductive detectors have been fabricated in an interdigital structure on GaAs substrates to improve optical coupling for fiber applications. A detector was designed with metal fingers 5 μm by 240 μm long with a 5 μm separation (160 μm by 200 μm total) [67]. When biased to 20 volts, the response was 50 ps. A monolithic photoreceiver was designed which used an interdigitated npn photoconductive detector to achieve a 200 GHz gain-bandwidth product [68]. Interdigital structures fabricated with heterojunction material have also been investigated by Claspy *et al.* for applications in monolithic microwave circuits [69, 70]. Devices were grown on GaAs substrates with a $Ga_{0.7}Al_{0.3}As$ layer and with the separation between electrodes varied from 1 μm to 5 μm. S-parameter measurements were obtained in the frequency range of 2 to 8 GHz. These devices rolled off at 2 GHz with small deviations from typical first order roll-offs of 20 dB/decade due to traps. Interdigital heterostructure detectors have also been integrated into HEMT based monolithic receivers with a gain-bandwidth product of 5 GHz [71]. The major limitation with interdigitated or MSM detectors is that much of the light is reflected by the metalization. Darling *et al.* [72] overcame this limitation by developing a mesa etched n^+ epitaxial layer as the low resistance contact to improve the responsivity 5 to 6 times over compatible MSM detectors. Pang *et al.* reported on a modulation doped $GaAs/Ga_{0.3}Al_{0.7}As$ photoconductive detector with a responsivity of 2.5 A/W corresponding to a gain of 3 [73]. Back-side illumination of $Ga_{0.47}In_{0.53}As$ photoconductive detector on InP substrates has shown a 1.5 dB improvement over front side illumination due to reductions in reflections when used with a 1.3 μm light source [74].

4.2 PIN Photodetectors

Bar-Chaim designed a GaAs based PIN device with a transparent p+ AlGaAs layer suitable for monolithic integration [75]. A 3 dB frequency response of 2.5 GHz was measured, and a responsivity of 0.4 mA/mW was achieved. PIN photodetectors based on InGaAs latticed-matched to InP substrates for the 1.3 to 1.6 μm region have been developed [76]. Improved response of InP based devices has been demonstrated by back-side illumination [77].

Cinguino fabricated a low operating voltage PIN with a pulse response of 211 picoseconds and a minimum quantum efficiency of 40% [78]. A packaged InGaAs PIN device with a frequency response into the millimeter wave frequency region [79] was made by reducing the intrinsic layer thickness from a length of 2.7 μm to 0.5 μm, and by reducing the device capacitance using a 10 μm radius. A high speed PIN photodetector with a 58 GHz bandwidth and with the device housed across a tapered waveguide for millimeter wave applications was reported by Bowers *et al.* [80]. Miura *et al.* have developed a planar InP/GaInAs PIN photodiode fabricated on a semi-insulating InP substrate [81] for electro-optic integrated circuit applications. The diode exhibited a 14 GHz cut-off frequency.

4.3 Schottky Photodetectors

Many researchers have developed devices based on semi-insulating GaAs. Rav-Nov *et al.* fabricated a small area photodiode (8 μm by 15 μm) with a bandwidth in excess of 9 GHz [82] on semi-insulating GaAs. The quantum efficiency was 15% at 840 nm. A device with a 3 dB bandwidth of 100 GHz has been reported by Wang *et al.* [83, 84], obtained by reducing capacitance and diffusion effects with the use of proton bombardment. Quantum efficiency was also enhanced with the use of a semi-transparent 100 Angstrom Pt Schottky barrier. Sugerta *et al.* developed a Schottky barrier photodetector with a gain of 100 [85] due to photogenerated hole accumulation at the barrier.

An interdigitated structure was made with 0.5 μm wide Al Schottky barrier metalization and an electrode spacing of 1.5 μm on a 5.0 μm thick n-type GaAs [86]. Figurero *et al.* have reported an interdigitated heterostructure based on a GaAs/$Ga_{0.6}Al_{0.4}As$ structure displaying a rise and fall time of 50 ps and 60 ps respectively, a capacitance of 0.3 pf, and a dc responsivity of 0.3 A/W at 0.83 μm. Heterostructures for longer wavelengths have also been fabricated [87] with a semi-transparent Schottky contact on p-type $Ga_{0.47}In_{0.53}As$ demonstrating rise and fall times of 15 ps in the region of 1.3 μm to 1.6 μm [88].

4.4 Phototransistors

There is a growing interest in using HBTs as optical detectors for monolithic integration of optical and microwave circuits. The HBT is designed with a wide band gap emitter so that it is transparent to the optical signal. The wide band gap emitter allows more light to be absorbed into the base region where the induced base photocurrent is multiplied by h_{fe} (current gain). Heterojunction devices with GaAs/GaAlAs interfaces have demonstrated optical gains up to 100 and response times of 2 ns in the optical wavelength region of 0.8 to 0.9 μm [89]. The photocurrent in high gain HBTs was shown to be a linear function of the illumination in the range of 100 to 1000 lx [90]. Beneking *et al.* [91] reported the wavelength response of a wide-gap-emitter transistor in which the response peaked at 700 nm with an associated responsivity of 700 A/W. Campbell *et al.* reported an optical gain of 40 with an input power of 1 nW in the wavelength region of 0.95 to 1.6 μm [92]. They also found that the sensitivity was 1000 times higher than in previously reported devices. Optical gains of 100 have been achieved with higher incident optical power levels [93].

Fritzsche *et al.* found that a base connection is essential for high speed operation at low optical power levels [94]. The response time of their device was less than 2 ns with an optical gain of 6. The high speed and low optical gain is indicative of a gain-bandwidth limitation that is ultimately reduced by the collector capacitance and the load resistor. As current gains improve and state-of-the-art input capacitance is reduced, the HBT may yield better sensitivity than the PINFET combination at frequencies in excess of 1 GHz

[95]. Noise analysis and measurements, based on the shot noise of the collector and base, and on the thermal noise of the load resistor, have shown that the HBT is comparable to the PIN-FET [96].

Wang *et al.* [97, 98, 99] reported a monolithic GaAs/GaAlAs phototransistor/receiver with the operation of the heterojunction phototransistor described as a photodiode driving a transistor amplifier. The results indicate a bandwidth of 80 MHz and a minimum detectable power of 1 μW.

4.5 Summary

Several photodetector structures used in high speed fiber optic links have been reviewed. These detectors, based in GaAs and InP material, dominate microwave applications. Photoconductive devices possess internal gain and are simple in design and fabrication. PIN devices have useful frequency responses to 60 GHz and can be integrated in complex monolithic structures. A simpler approach for monolithic integration is to use a Schottky junction photodetector. The Schottky junction photodetector does not require a p-type layer as in the PIN, and it has been used to 100 GHz. The quantum efficiency of the Schottky junction photodetector is much lower than the PIN due to the planar configuration and metalization reflection of the optical signals.

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